Review

Potential Co-Disposal of Food Waste and Sewage Sludge in South Africa: A Review

Shalongo Angula [1], *, Teboho Mofokeng [1] and Moses Basitere [1], David Ikumi [1]

[1] Water Research Group, Department of Civil Engineering, University of Cape Town, Rondebosch, 7701, Cape Town, South Africa
* Correspondence: sttangula@gmail.com

Abstract: The emergence of the circular economy, and the evolving paradigms in the treatment and management of wastewater, have opened up an opportunity for co-digestion of organic waste (i.e., food waste) with sewage sludges to enhance resource recovery at wastewater treatment plants (WWTPs). This paper reviewed the potential for anaerobic co-digestion of food waste and sewage sludges, as well as alternative sustainable food waste handling systems in South Africa. The promotion of the circular economy by the latest national solid waste management strategy and the ongoing efforts for resource recovery by the wastewater sector suggests that anaerobic co-digestion of food waste and sewage sludge is possible in South Africa. Furthermore, an integrated food waste disposer (FWD) system was identified as a sustainable alternative for food waste handling. To formulate a roadmap for future food waste and sewage sludge co-digestion implementation, a multi-disciplinary investigation is required to bridge the literature gap.

Keywords: Resource recovery; circular economy; food waste; anaerobic co-digestion

1. Introduction

The research on best practice design and operation of wastewater treatment plants (WWTPs) has intensified over the past decade. This intensification results from the need for adaptation of existing and future infrastructure to declining resources, population increase and climate change. Hence, there have been new concepts of the circular economy (which include the changing paradigms of converting future wastewater treatment systems to water and resource recovery facilities (WRRFs)) and the development of climate-resilient infrastructure (including the need to convert water and energy scarce areas into water and energy-sensitive regions). To increase the potential for recovery of resources (mainly water, nutrients and energy), the design and operation specifications of current WWTP systems have to account for the fate of products that would be generated due to the treatment process [1,2]. Typical examples of resource recovery include the utilisation of the anaerobic digestion (AD) unit process for sludge treatment, which produces useful products such as biogas (which can be converted to energy) and nutrients such as nitrogen and phosphorus (used in fertilisers).

In support of the circular economy concept, the South African government has adopted a third National Waste Management Strategy (NWMS) that seeks to divert organic waste (i.e., food waste) from landfills [3]. Globally, the shift towards the circular economy in the waste sector is driven by the resource-intensive nature of landfills and their associated environmental problems, such as greenhouse gas emissions, leachate production and terrible odours [4,5]. As a result, there have been deliberate efforts to seek alternative sustainable solutions for organic waste management in South Africa and across the globe.

Anaerobic Digestion (AD) is one of the oldest technologies used in organic waste and wastewater treatment. The AD technology has remained popular to date because of its

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0530.v1

capability to significantly reduce volatile solids and the production of methane-rich biogas [6, 7]. Biogas generated from AD is a renewable resource that can be converted to electricity, which may, in turn, be used to power the AD system or fed into power supply grids. Most wastewater treatment plants (WWTP) employ AD for sludge treatment. Furthermore, it is reported that most AD systems have excess unutilised capacities, which result from water conservation efforts and slow population growth [8,9].

Anaerobic co-digestion of sewage sludge and organic waste presents a potential solution for organic waste management and underutilisation of AD systems. The anaerobic co-digestion strategy has been implemented at WWTPs in the United States (US) and Europe. In most cases, these WWTPs plants have been able to achieve energy sufficiency of up to 120% [10]. According to a review by Shen *et al.* [10], food waste is predominantly a co-substrate at WWTPs that have implemented full-scale co-digestion. This is because food waste is the most significant portion of the organic fraction of municipal solid waste (OFMSW). In addition, food waste is predominantly a biodegradable substance that releases methane (biogas) during its degradation [4].

Despite the overwhelming scientific evidence of the potential benefits of food waste and sewage sludge co-digestion, full-scale implementation is still a complex process. Nghiem *et al.* [8] identified five challenges to full-scale food waste and sewage sludge digestion, which include complex food waste handling systems, unclear food waste characterisation, the conflict between environmental and economic gains, shortage of policies, and lack of skill and technologies. These challenges need to be addressed in evaluating the feasibility of food waste and sewage sludge co-digestion.

Despite the growing body of research on food waste and sewage sludge co-digestion, there have been limited studies on food waste and wastewater co-digestion tailored explicitly to developing countries, including South Africa. Therefore, this review presents a vital contribution to South Africa's literature on the subject. This paper aims to review (1) the potential for diverting food waste to WWTPs, and (2) alternative sustainable systems for solid waste separation and food waste transport to treatment facilities.

2. Potential for Diverting Food Waste to WWTPs

The third South African NWMS, gazetted in 2021, has included the circular economy concept, which is driven by its potential to stimulate economic activities by diverting waste from landfills [3]. In addition, Godfrey *et al.* [3] identified organic waste (representing more than a third of the total general waste) as one category with a high potential for resource recovery. As discussed earlier, food waste is the most preferred organic waste for co-digestion. On the other hand, wastewater is generally accepted as the backbone of the circular economy in the water sector [11]. For this reason, there have been deliberate efforts in South Africa, particularly funded by the Water Research Commission (WRC) and *Deutsche Gesellschaft für Internationale* (GIZ), to investigate the potential for energy recovery in the wastewater treatment sector [12–14].

2.1 Food waste in South Africa

Food waste quantity, composition and quality[1] vary significantly from location to location due to varying income levels and types of diet [15]. Consequently, the quantity and quality of resources recoverable from food waste depend on the quality and quantity of food waste. Therefore, when considering the co-digestion of food waste and wastewater in South Africa, it is necessary to determine the local quantity and quality of food waste available. Furthermore, selecting suitable solid waste separation and food waste transport

[1] The quality of food waste refers to its composition and characteristics, which determine its easiness to be degraded in the AD systems.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0530.v1

systems requires a good understanding of the local food waste characteristics besides the existing or planned infrastructure and technologies. However, like in many developing countries, there is inadequate peer-reviewed literature on food waste in South Africa.

2.2 *Quantity of Food Waste*

Successive studies by by Nahman *et al.*, Nahman and de Lange, Oelofse and Nahman and de Lange and Nahman [16–19] made an effort to quantify the size and cost (opportunity cost) of food waste produced throughout the food supply chain in South Africa. According to these studies, over 30% of the food produced is lost along the food supply chain, with 5% of these losses occurring at the final stage of the supply chain (household). Food waste at earlier stages of the supply chain may be easily repurposed, but household food waste, in most cases, is discarded together with the rest of household solid wastes to landfills. However, these studies were primarily focused on food waste from a food security perspective. Therefore, the studies lacked a quantification of how much food waste is discarded to landfills.

Machate [20] raised concerns about the reliability of results obtained by Nahman *et al.*, Nahman and de Lange, Oelofse and Nahman, and de Lange and Nahman [16–19]. Machate [20] specifically questioned (1) the lack of a standard definition of food waste, which has resulted in inconsistency and interchangeable usage of the terms food waste and food loss, and (2) the lack of clarity about the stages in the food supply chain and the stage at which food losses are considered as food waste, and lastly, (3) the credibility of the methodology and assumptions used by these studies.

Other food waste-related studies in South Africa involving primary data collection include studies carried out by Cronje *et al*. and Oelofse *et al.* [21,22] in Northern Cape (Kimberly) and Gauteng (Johannesburg and Ekurhuleni) provinces, respectively. The two studies employed different data collection methodologies to quantify household food waste. In most cases, household food waste is discarded, with the rest of the household waste, to landfills as their final destination. These studies show that food waste represents a significant portion of household waste, as observed in other regions like Hong Kong and the United Kingdom (UK) [23,24]. However, studies done in South Africa were not conducted from a resource recovery perspective; thus, critical information such as quantity and quality of food waste, potential resource recoverable and strategy for food waste transportation is lacking.

2.3 *Waste and Food Waste Management*

Although recycling has existed in South Africa for many decades, source separation of waste is still not widely practised. Thus, the informal sector facilitates the collection of recyclable materials, which pick waste either by kerbside or from landfill sites, a system known as “separation-outside-source” [25]. However, Godfrey et al. [3] believe that this type of collection results in contamination[2] which reduces the recycling output rate. Moreover, the putrescible nature of food waste and other organic waste makes them unsuitable for manual handling by informal waste pickers. Certainly, much of organic and food waste is left to decompose in landfills. However, in support of its circular economy ambitions, the South African government plans to intensify waste source separation initiatives.

The current setup of food waste handling is not compatible with the circular economy or co-digestion of food waste and sewage sludge, to be specific. The processes of food

[2] Contaminated waste is a mixture of waste from different waste categories including those that are not suitable for resource recovery. As a result, they have to go through either physical, biological or chemical (sometimes combined) pre-treatment

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0530.v1

waste collection, transport and pre-treatment have been cited as some of the major challenges for anaerobic co-digestion of food waste and sewage sludge [8,26]. This is because anaerobic digesters are very sensitive and require a well-coordinated influent feed supply (both quantity and quality) to ensure efficient performance. Therefore, when considering diverting food waste for co-digestion at the WWTP, it needs to be ensured that quality food waste is made available.

2.4 Anaerobic Digesters

It is believed that over 100 WWTPs in South Africa use AD technology for sludge treatment [14]. In addition, it was recorded that about half of the sludge generated by South Africa's WWTPs is anaerobically digested [27]. According to van der Merwe-Botha et al. [14], more than R140 million can be saved every year by implementing biogas recovery at WWTPs utilising AD systems in South Africa. However, Ferry and Giljova [12] cautioned that most AD systems in the country are designed and operated for sludge treatment and therefore require to be retrofitted for their utilisation to include biogas recovery. Furthermore, over 70% of the WWTPs with AD systems have feasible potential to invest in biogas recovery potential using the combined heat and power (CHP) technology [12,14]. One of the factors used to assess the feasibility of biogas recovery at these WWTPs was the potential for co-digestion, to utilise excess digester capacities [12]. However, because the concept of co-digestion of sewage sludge is not common in South Africa, Ferry and Giljova [12] appealed for more investigation on the viability of co-disposal of organic waste with sewage sludge in South Africa.

3. Solid Separation and Food Waste Transport Systems

The collection and transport of food waste to treatment plants determines the quality and quantity of food waste available for resource recovery. Therefore, a suitable food waste handling system must be evaluated and identified when considering food waste and sewage sludge co-digestion. This section reviews and discusses three leading examples of sustainable food waste handling (collection and transport) systems concerning notable full-scale or pilot-scale case studies implemented in various parts of the world. Two of the three food waste handling systems reviewed are established, while one is still considered novel. However, both systems have been implemented in different parts of the world, either in full-scale or pilot-scale projects. Besides the three food waste handling systems reviewed in this paper, no other system was used in food waste and sewage sludge co-digestion projects and found in peer-reviewed literature.

The inclusion of case studies in the review article is intended to highlight the experience from full-scale and pilot-scale projects, which are valuable lessons for developing countries considering the implementation of sewage sludge and organic waste co-digestion. Although co-digestion of food waste and sewage sludge is being practised in various parts of the world, case studies selected as a reference in this review are only located in Italy, Sweden, Germany and the USA. These case studies were selected due to their (1) availability of information in English scholarly journals and (2) ambitious and rigorous full-scale or pilot-scale implementation strategies. Afterwards, a strength, weakness, opportunity and threat analysis (SWOT) analysis tool [28] was applied to evaluate the internal issues (strengths and weaknesses) and external issues (opportunities and threats) of each system. In addition, the SWOT analysis took into account the possible benefits and challenges resulting from the implementation and operation of each type of system within the context of their application to South Africa and other developing countries.

3.1 Decentralised System

Decentralised food waste and sewage sludge co-digesting WWTPs receive food waste, with transport modes differing from site to site and varying frequencies. Upon their arrival at a WWTP, food waste must undergo physical and mechanical pre-treatment before co-digesting with sewage sludge. The pre-treatment process includes removing coarse contaminants and inert materials (i.e. plastics, glass and bones) and grinding food waste into smaller particles [29,30]. The pre-treatment products are a liquid food waste slurry and residual inert solid waste. The food waste slurry is stored in storage tanks before discharging to the WWTP's AD system for co-digestion with the wastewater sludge. The residual inert solid waste is dewatered on-site before being sent to landfills or incinerating facilities.

3.1.1 Case Studies

The Rovereto plant (Italy) and East Bay Municipality Utility District (EBMUD) WWTP (USA) are examples of decentralised food waste and wastewater co-treatment plants with nearly similar operations [8,29]. First, the food waste is collected from local facilities that source separate their food waste, which is then trucked to the WWTP, equipped with on-site food waste pre-treatment facilities [31,32]. The pre-treated food waste is then stored in storage tanks before pumping to the WWTP's anaerobic digester. Storing the pre-treated food waste slurry is important because it helps feed the anaerobic digester with a consistent flow over time, which is vital for stable AD operation. After implementing co-digestion with food waste, the EBMUD plant became the first-ever energy-neutral plant in the world [29]. Figure 1 shows the schematic process of the two plants discussed above.

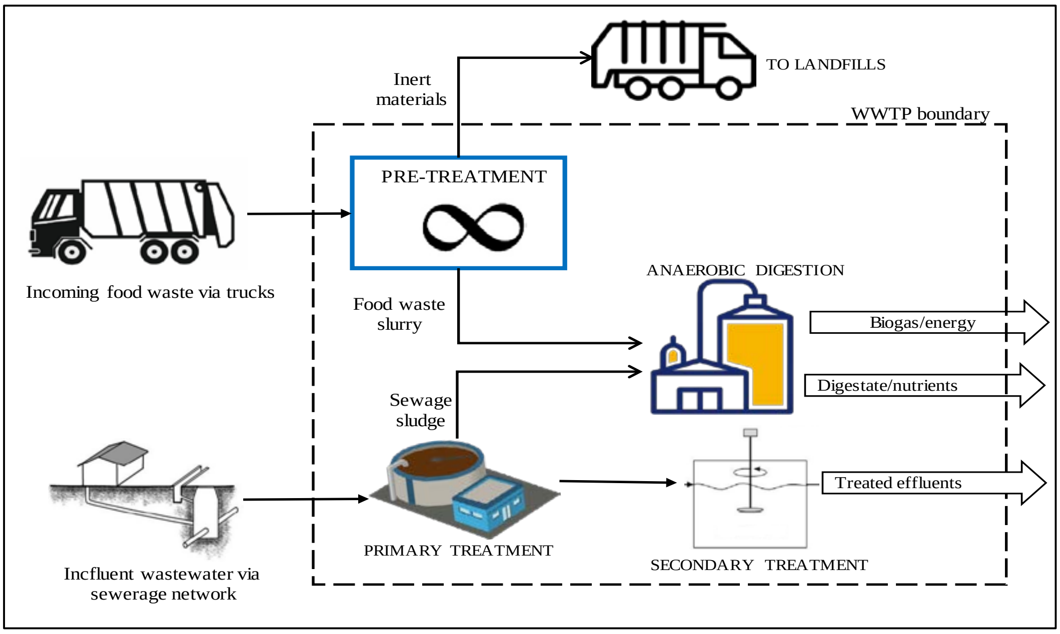

Figure 1. Illustration of food waste and sewage sludge co-digestion in a decentralised system

In contrast to the Rovereto and EBMUD plants discussed above, other decentralised co-digesting plants only accept liquid food waste such as brewery, dairy wastes and pre-treated food waste from centralised food waste processing plants. Accepting liquid food waste eliminates the need for an on-site pre-treatment process. Food waste pre-treatment is a complex, capital, and energy-intensive process [8,33]. An example is the Moosburg WWTP (Germany), which receives up to seven liquid food waste co-substrates from different sources, including pre-treated food waste from a centralised food processing plant [34].

3.1.2 SWOT Analysis

Table 1 summarises the SWOT analysis of a decentralised food waste and wastewater co-digestion system.

Table 1. SWOT Analysis for a decentralised food waste and wastewater co-digestion system

Strength	o Contribute to the circular economy o One-way system (i.e., from source to WWTP), making it less complex
Weakness	o Processing of food waste plant is the capital, labour and skill intensive - requires economy of scales o Consistency of food waste quality and quantity depends on collection and pre-treatment efficiency o Loss of organic content (energy) during transportation o Manual handling of food waste is unhygienic and causes offensive odours o Need to invest in storage and transport facilities (i.e., trucks and storage bins) o The energy required for pre-treatment and transportation of food waste o Food waste requires pre-treatment before co-digestion o Requires energy for pre-treatment
Opportunities	o Creation of employment in the food waste supply chain and operation of the pre-treatment plants o Potential to significantly reduce organic waste at landfills
Threats	o Increased activity of trucks will result in unimpressive aesthetic, traffic loads and noise pollution o Inefficient handling of food waste can threaten bad odours and disease risks from pathogens o Emission of GHG throughout the collection and transport process

3.2 Centralised Ssystem

On-site food waste pre-treatment, as in the case of the EBMUD and Rovereto WWTPs (discussed in Section **Error! Reference source not found.**), is a capital and labour-intensive process [8]. Therefore, on-site food waste processing is suitable for large WWTPs that have achieved or can achieve economies of scale within short periods. Centralised food waste processing facilities' primary business is to pre-treat food waste sourced from various industries and make the pre-treated food waste slurries available to resource/nutrient recovery facilities, including co-digesting WWTPs. In addition, since centralised food waste facilities are built to pre-treat rich-organic substrates, they offer flexibility and capacity to co-process food waste with other types of organic waste, if available. In terms of operation, it is similar to the operation of an on-site pre-treatment plant discussed above. Pre-treatment includes removing inert materials by mechanical processing, sanitation, and removing fats, oil and grease (FOG) by centrifuging, then storing and transporting the pre-treated slurry to WWTPs [8,35].

3.2.1 Case Studies

The Oberding food waste processing plant (Germany) is an outstanding example of a centralised food waste processing plant [35,36]. This is because the Oberding plant has a modernised design and operation, including specialised collection trucks and automated machinery. Food waste is hauled, via trucks, from various sources (household and commercial customers) within a catchment radius of 200 km from the plant. Pre-treated food waste slurry is then made available mainly to the local WWTP (Moosburg) for co-digestion in the AD system to enhance biogas recovery. In addition, surplus pre-treated food waste at Oberding is fed to other local resource and nutrient recovery plants. Pre-

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0530.v1

treated waste is transported in tankers with a capacity to maintain a temperature of above 90⁰C to prevent food waste from solidifying [8]. In addition, the plant recovers up to 7% of FOG from the liquid food waste during pre-treatment via centrifuge, which reduces the risk of solidification during storage and pumping problems. The operation flow of the Oberding plant is summarised in **Figure 2**.

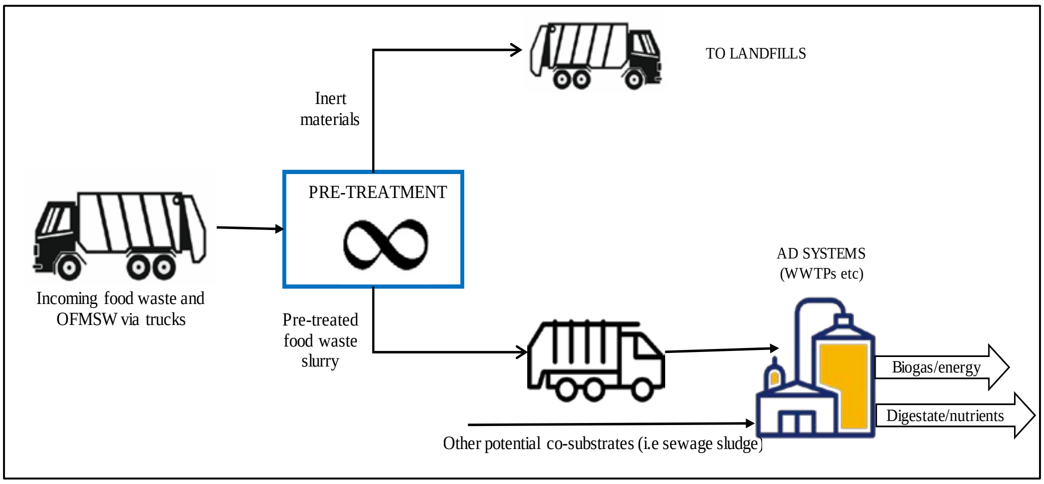

Figure 2. A typical process flow diagram of a centralised food waste processing plant

Two full-scale case studies of co-digestion of pre-treated food waste obtained from the Oberding plant and wastewater were carried out at Grüneck and Moosburg WWTPs [34,35]. At Grüneck WWTP, the AD organic loading was increased by 20%, with food waste resulting in a 16% energy recovery increase [35]. Unfortunately, food waste also resulted in downstream problems, including solids sedimentation, inconsistent biogas quality, and reduced sludge dewaterability [35]. At Moosburg WWTP, wastewater, food waste, and dairy waste were co-digested at a 35:47:18 ratio [34]. This co-digestion increased methane potential by 300%. However, similar to the Grüneck plant, the Moosburg plant also encountered problems after introducing food waste to its operation. Problems encountered include increased nitrogen backload, solid sedimentation in the digester, reduced solid retention time, and reduced sludge dewaterability [34].

3.2.2 SWOT Analysis

Table 2 shows a summary of the SWOT analysis of a centralised food waste and wastewater co-digestion system.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0530.v1

Table 2. SWOT analysis for a centralised food waste and wastewater co-digestion system

Strength	o Contribute to the circular economy o Less capital intensive compared to WWTP on-site food waste pre-treatment o Flexibility to source from a wide range of organic waste streams o Easy to control consistency in food waste quantity and quality, which is important for WWTP operation
Weakness	o Manual handling of food waste is unhygienic and causes offensive odours o Loss of organic content (energy) during transportation o Only suitable for large cities that have a variety of organic waste streams o Processing of food waste plant is the capital, labour and skill intensive-requires economy of scales o Need to invest in storage and transport facilities (i.e., trucks and storage bins) o Food waste requires pre-treatment before co-digestion o Requires energy for pre-treatment
Opportunities	o Pre-treated waste is made available to various resource recycling facilities and thus promote competition in the economy o Employment creation throughout the food waste supply chain and plant operation o Conserve landfill space o Reduction of organic waste to landfills
Threats	o Transportation of hot liquid food waste from the central plant to end-users on public roads poses a danger to other road users o Inefficient handling of food waste can threaten bad odours and disease risks from pathogens o Increased activity of trucks will result in unimpressive aesthetic, traffic loads and noise pollution o Emission of GHG during transportation of food waste between source and central plant

3.3 Integrated Food Waste Disposer System

Food waste disposers (FWD) or in-sink macerators are devices built on the underside of kitchen sinks that grind food waste into fine particles and flush the effluent into the sewerage system [23]. The FWDs have been in existence since the 1920s and have been used as an effective method for diverting food waste from landfills [4]. The FWDs are mostly used in the USA, New Zealand, and Australia, where respectively, 50%, 30%, and 20% of the households use FWDs [37]. However, FWDs are still novel to the rest of the world, and their impacts on the sewer system and the WWTPs at large have not been well established. As a result, the use of FWDs is either banned or regulated in several European countries due to a poor understanding of the impact of ground food waste on the sewer network and WWTPs infrastructure and processes [4,23]. Additionally, the consequences of adopting FWDs will vary from location to location due to variations in food waste characteristics and distinctions in wastewater treatment networks and operations [38].

Since it has also been widely proven that co-digestion of food waste and wastewater can enhance biogas recovery, efforts are being made to investigate the potential to use FWD to transport the food waste to WWTPs. These efforts include lab-scale experiments [39], plant-wide models [40], and full-scale studies [41,42]. However, while most studies confirmed biogas enhancement from the utilisation of FWDs, part of the scientific and technical communities still have objections to implementing this technology. The objec-

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0530.v1

tions are due to the energy and water consumption of FWDs, potential corrosion in concrete pipes, clogging due to oil and grease loads, poor effluent qualities, settling in sewerage systems and the potential need to retrofit sewer and WWTPs infrastructure [36,43,44].

Some studies also contradict the above challenges. For example, the New York City (NYC) Department of Environmental Protection [45] reported no clogging, fouling, or sedimentation problems resulting from the use of FWDs. Additionally, Nilsson *et al*. and Battistoni *et al*. [46,47] argued that no settling problems result from FWDs. Thus, as a result of contradicting literature, and the possible need to retrofit sewer systems, there appears to be a resistance to large-scale implementation of FWDs.

3.3.1 Case Study: FWD to WWTP System

Battistoni *et al*. [47] carried out a pilot-scale case study to investigate the impact of FWD on a WWTP. The study area was a mountain village in Italy with a population of about 250 people, and FWDs were installed in 67% of the households. No significant hydraulic overloads or solids sedimentations were observed in sewer pipes due to FWD installation, which is in line with the findings of [46]. As expected, food waste increased the organic and nutrient loads to the WWTP. In terms of WWTP process performance, chemical oxygen demand (COD; used to measure organics) and nitrogen (N) removal increased while aeration energy demand decreased by 39%. Aeration energy demand decreased due to increased denitrification efficiency (i.e., there was increased readily biodegradable substrate to provide electron donors during the anoxic cycle of treatment), which allowed the utilisation of nitrogen-bound oxygen. The WWTP used in this case study does not have an anaerobic digester; therefore, biogas recovery potential was not evaluated. Nevertheless, this study's findings showed how FWD technology can be attractive in places where source separation of food waste is not practical, such as small decentralised towns.

3.3.2 Case Study: Tank-connected FWD System

To combat the potential challenges for the sewerage system and WWTP caused by FWDs, while retaining their benefits, a novel tank-connected FWD system was adopted for a full-scale study in Malmo, Sweden [48]. In this system, the FWDs are connected to kitchen sinks. The houses are built with separate drain systems, one from the bathroom directly to the WWTP and one from the kitchen sinks connected to a local separation tank. The Separation tank is made up of two compartments. In the first compartment, particulate food waste settles at the bottom, which is later collected by trucks and transported to biogas plants. The second compartment removes the sludge and FOG. Finally, excess water containing soluble food waste is discharged to the WWTP. The system process is illustrated in **Figure 3**.

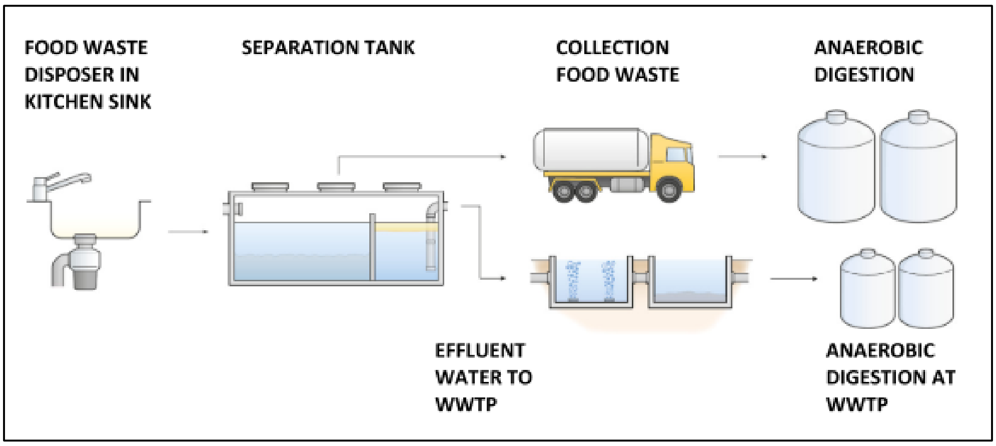

Figure 3. A tank-connected FWD system (Adapted from Bernstad et al. [48] by Davidsson et al. [42]. Copyright 2013 by Elsevier. Reprinted with permission.)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0530.v1

Bernstad Saraiva *et al.* [41] carried out a lifecycle assessment to compare the tank-connected FWD and manual food waste separation systems in terms of greenhouse gas emission and primary energy utilisation. The assessment results show that the tank-connected FWD system has a low GHG emission potential but high capital energy costs. Due to the high energy requirement for the tank-FWD system, the manual food waste separation system was recommended as a suitable method. However, this study overlooked various factors such as pre-treatment of manually collected food waste which is energy-intensive and requires ample space. Besides, the study left many unanswered questions, such as the effect of increased nutrients and organic loads on the WWTPs, later treatment of effluent from the tank-connected system, wastewater treatment in the separation system, and energy recovery potential for each system. Therefore, a holistic approach can add more value to such a study.

Following up on the study by Bernstad Saraiva *et al.* [41], Davidsson *et al.* [42] carried out a system-wide technical evaluation of the tank-connected FWD system to optimise biogas nutrient recovery from food waste. The study found that 28% of the food waste entering the tank leaves with the effluent to the WWTP, while 38% needs to be trucked to the AD systems. The rest is the residual waste that is transported to landfills. The biomethane potential (BMP) results from the food waste collected from the tank indicate that the tank-connected FWD system enhances biogas production and can be optimised for biogas recovery. However, the recovery of nutrients was not practical because only small fractions (about 20%) of phosphorus and nitrogen were recovered from the food waste collected from the tank. Low fractions of the nutrients could be because nutrients are mainly in a soluble form and therefore end up in the effluent that escapes to the WWTP. However, the study did not evaluate the potential recovery of nutrients and energy of the soluble food waste contained in the effluent that goes to the WWTPs.

3.3.3 SWOT Analysis

Error! Reference source not found. shows a summary of the SWOT analysis of a co-digestion system that is linked to FWD.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0530.v1

Error! Reference source not found.. shows a summary of the SWOT analysis of a co-digestion system that is linked to FWD

Strength	o No organic loss during transportation, resulting in better energy recovery o Suitable for small and decentralised towns where collection where source separation and collection by trucks is practical o Contribute to the circular economy o Does not require pre-treatment of food waste o No GHG emission during transportation
Weakness	o Increased sludge production at WWTP that need to be safely disposed o Inadequate knowledge on the impact of FWD on sewer network and WWTP performance (i.e., sedimentation, clogging etc.)
Opportunities	o FWD are a convenience for hygiene in households o Stimulate economic activities (i.e., innovating, manufacturing and installing FWD) o Conserving landfill space
Threats	o Existing sewer infrastructures may not have the capacity to handle additional loads o Increased potable water usage for grinding and flushing food waste and corresponding influent flow rates at WWTPs o Loss of income to the unskilled workers and informal sector who relied on manual waste sorting o Increased energy demand to power FWD

4. Conclusion and Recommendations

4.1. *Conclusion*

This paper comprehensively reviewed the potential for co-digestion of food waste and sewage sludge at wastewater treatment plants (WWTPs) in South Africa. Furthermore, three potential alternative sustainable systems for solid waste separation and food waste transport to WWTPs were reviewed and analysed concerning case studies selected from four countries: Germany, Italy, Sweden and USA. Given that the management of organic waste, which includes food waste, fits within the desired objectives of the circular economy concept, this review should prove valuable to environmental managers and policymakers in developing countries seeking to divert organic waste from landfills. Further, this review provides a foundation for future research toward implementing resource recovery from wastewater and organic wastes in South Africa and other developing countries.

The following concluding points have been drawn from the literature review:

- There is limited uptake of large-scale implementation of sewage sludge and food waste co-digestion worldwide due to technical challenges and the co-digestion concept being in its infancy stage
- Anaerobic co-digestion of sewage sludge and organic waste has not been implemented in South Africa yet. However, the promotion of a circular economy by the national solid waste management strategy, together with the ongoing efforts for wastewater resource recovery by the water sector, suggests that co-digestion of sewage sludge and organic waste is possible.
- Manual source separation of food waste is associated with a complex food waste pretreatment process and threatens offensive odours if not appropriately handled.
- The integrated system, which uses a food waste disposer (FWD) to discharge food waste to sewer systems, eliminates the problem of bad odours and eliminates the

need for food waste pre-treatment, making FWDs a potentially sustainable solution for diverting food waste from landfills.

4.2. Recommendations

For a country to formulate a roadmap for future development in diverting food waste from landfills to WWTPs in support of a circular economy, it is recommended that a multidisciplinary investigation should be carried out. This investigation should include:

- A quantity and quality characterisation of "real" food waste
- A quantitative case study on the feasibility of different food waste collection and transport systems
- The possible impact of FWD on potable water and energy usage and sewage network
- Enabling policies and legislation to accelerate the implementation of resource recovery from organic waste
- Social, economic and environmental impacts of diverting food waste to WWTPs
- Environmental benefits versus actual economic values of sewage sludge and food waste co-digestion

5. Patents

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, D.I. and S.A.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Conflicts of Interest: The authors declare no conflict of interest

References

1. Montwedi, M.; Munyaradzi, M.; Pinoy, L.; Dutta, A.; Ikumi, D.S.; Motoasca, E.; Van der Brugen, B.; and Van der Bruggen, B. Resource recovery from and management of wastewater in rural South Africa: Possibilities and practices. *J. Water Process Eng.* **2021**, *volume* 40, p. 101978. [doi: 10.1016/j.jwpe.2021.101978]
2. Ikumi, D.; Maake, V.; Quevauvilliers, M.; Thela, N.; Dutoit, J.; Oodally, A.; Coothen, Y.; Paleker, I.; Maganga, E.; and Governder, N. Including the fate of chemical precipitants and other products of waste resource recovery facilities in their strategic design and operation Project No. K5/2839. , 2022.
3. Godfrey, L.; Roman, H.; Smout, S.; Maserumule, R.; Mpofu, A.; Ryan, G.; and Mokoena, K. Unlocking the Opportunities of a Circular Economy in South Africa. , in *Circular Economy: Recent Trends in Global Perspective*, Ghosh S. K. and Ghosh S. K. Eds. Springer: Singapore, 2021, pp. 145–180.; [doi: 10.1007/978-981-16-0913-8_5]
4. Iacovidou, E.; Ohandja, D.; Gronow, J.; Iacovidou, E.; Ohandja, D.; and Gronow, J.A.N. The Household Use of Food Waste Disposal Units as a Waste Management Option : A Review. *Crit. Rev. Environ. Sci. Technol.* **2012**, *volume* 42:14, pp. 1485–1508. [doi: 10.1080/10643389.2011.556897]
5. Stillwell, A.S.; Hoppock, D.C.; and Webber, M.E. Energy recovery from wastewater treatment plants in the United States: A case study of the energy-water nexus. *sustainability* **2010**, *volume* 2, pp. 945–962. [doi: 10.3390/su2040945]
6. Van Lier, J.B.; Mahmoud, N.; and Zeeman, G. Anaerobic wastewater treatments. , in *Biological Wastewater Treatment: Principle, Modelling and Design*, Henze M., van Loosdrecht M. C. M., Ekama G. A., and Brdjanovic D. Eds. IWA Publishing: London, UK, 2008.;
7. Sötemann, S.W.; van Rensburg, P.; Ristow, N.E.; Wentzel, M.C.; Loewenthal, R.E.; and Ekama, G.A. Integrated chemical / physical and biological processes modelling Part 2 - Anaerobic digestion of sewage sludges. *Water Sci. Technol.* **2005**, *volume*

31, pp. 545–568. [doi: 10.2166/wst.2006.553]

8. Nghiem, L.D.; Koch, K.; Bolzonella, D.; and Drewes, J.E. Full scale co-digestion of wastewater sludge and food waste: Bottlenecks and possibilities. *Renew. Sustain. Energy Rev.* **2017**, *volume* 72, pp. 354–362. [doi: 10.1016/j.rser.2017.01.062]
9. Arnell, M.; Astals, S.; Åmand, L.; Batstone, D.J.; Jensen, P.D.; and Jeppsson, U. Modelling anaerobic co-digestion in Benchmark Simulation Model No. 2: Parameter estimation, substrate characterisation and plant-wide integration. *Water Res.* **2016**, *volume* 98, pp. 138–146. [doi: 10.1016/j.watres.2016.03.070]
10. Shen, Y.; Linville, J.L.; Urgun-Demirtas, M.; Mintz, M.M.; and Snyder, S.W. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs. *Renew. Sustain. Energy Rev.* **May 2015**, *volume* 50, pp. 346–362. [doi: 10.1016/j.rser.2015.04.129]
11. Voulvoulis, N. Water reuse from a circular economy perspective and potential risks from an unregulated approach. *Curr. Opin. Environ. Sci. Heal.* **2018**, *volume* 2, pp. 32–45. [doi: 10.1016/j.coesh.2018.01.005]
12. Ferry, A. and Giljova, S. Biogas potential in selected waste water treatment plants: Results from scoping studies in nine municipalities. , Pretoria, 2015. [Online]. Available: https://www.cityenergy.org.za/uploads/resource_323.pdf
13. Musvoto, E.; Nomvuselelo, M.; Hazel, M.; and Mackinstosh, A. Energy recovery from wastewater sludge - a review of appropriate emerging and estabablished technologies for the South African industry. , Gezina, 2018. [Online]. Available: www.wrc.org.za
14. van der Merwe-Botha, M.; Juncker, K.; Visser, A.; and Boyd, R. Guiding Principles in the Design and Operation of a Wastewater Sludge Digestion Plant with Biogas and Power Generation. , 2016. [Online]. Available: http://www.wrc.org.za/Knowledge Hub Documents/Research Reports/TT 681-16.pdf
15. Fisgativa, H.; Tremier, A.; and Dabert, P. Characterizing the variability of food waste quality: A need for efficient valorisation through anaerobic digestion. *Waste Manag.* **Apr. 2016**, *volume* 50, pp. 264–274. [doi: 10.1016/j.wasman.2016.01.041]
16. Nahman, A.; de Lange, W.; Oelofse, S.; and Godfrey, L. The costs of household food waste in South Africa. *Waste Manag.* **2012**, *volume* 32, pp. 2147–2153. [doi: 10.1016/j.wasman.2012.04.012]
17. Nahman, A. and de Lange, W. Costs of food waste along the value chain: Evidence from South Africa. *Waste Manag.* **2013**, *volume* 33, pp. 2493–2500. [doi: 10.1016/j.wasman.2013.07.012]
18. Oelofse, S.H.H. and Nahman, A. Estimating the magnitude of food waste generated in South Africa. *Waste Manag. Res.* **2013**, *volume* 31, pp. 80–86. [doi: 10.1177/0734242X12457117]
19. de Lange, W. and Nahman, A. Costs of food waste in South Africa: Incorporating inedible food waste. *Waste Manag.* **2015**, *volume* 40, pp. 167–172. [doi: 10.1016/j.wasman.2015.03.001]
20. Machate, M. The conundrums of the estimated magnitude of food waste generated in South Africa. *Int. J. Sustain. Dev. Plan.* **2020**, *volume* 15, pp. 893–899. [doi: 10.18280/ijsdp.150613]
21. Cronje, N.; van der Merwe, I.; and Muller, I.-M. Household food waste: A case study in Kimberly, South Africa. *J. Consum. Sci.* **2018**, *volume* 46, pp. 1–9.
22. Oelofse, S.; Muswema, A.; and Ramukhwatho, F. Household food waste disposal in South Africa: A case study of Johannesburg and Ekurhuleni. *S. Afr. J. Sci.* **2018**, . [doi: 10.17159/sajs.2018/20170284]
23. Thomas, P. The effects of food waste disposers on the wastewater system : a practical study. *Water Environ. J.* **2011**, *volume* 25, pp. 250–256. [doi: 10.1111/j.1747-6593.2010.00217.x]
24. Zan, F.; Dai, J.; Hong, Y.; Wong, M.; Jiang, F.; and Chen, G. The characteristics of household food waste in Hong Kong and their implications for sewage quality and energy recovery. *Waste Manag.* **2018**, *volume* 74, pp. 63–73. [doi: 10.1016/j.wasman.2017.11.051]
25. Samson, M. Whose Frontier is it Anyway? Reclaimer "Integration" and the Battle Over Johannesburg's Waste-based Commodity Frontier. *Capital. Nature, Social.* **2020**, *volume* 31, pp. 60–75. [doi: 10.1080/10455752.2019.1700538]

26. Mehariya, S.; Kumar, A.; Karthikeyan, P.; Punniyakotti, E.; Wong, J.W.C.C.; Patel, A.K.; Obulisamy, P.K.; Punniyakotti, E.; and Wong, J.W.C.C. Co-digestion of food waste and sewage sludge for methane production: Current status and perspective. *Bioresour. Technol.* **2018**, *volume* 265, pp. 519–531. [doi: 10.1016/j.biortech.2018.04.030]
27. Snyman, H.G. Global atlas of excreta, wastewater sludge, and biosolids management: moving forward the sustainable and welcome uses of a global resource: South Africa. , in *Global atlas of excreta, wastewater sludge, and biosolids management: moving forward the sustainable and welcome uses of a global resource*, LeBlanc R. J., Metthews P., and Richard R. P. Eds. UN-Habitat, 2009, pp. 513–525.;
28. Diamantopoulou, P. and Voudouris, K. Optimization of water resources management using SWOT analysis: The case of Zakynthos Island, Ionian Sea, Greece. *Environ. Geol.* **2008**, *volume* 54, pp. 197–211. [doi: 10.1007/s00254-007-0808-5]
29. Hagey, P. Utility district ramps up food waste to energy program. *Biocycle* **2011**, *volume* 52, pp. 39–40.
30. Edwards, J.; Othman, M.; Crossin, E.; and Burn, S. Anaerobic co-digestion of municipal food waste and sewage sludge: A comparative life cycle assessment in the context of a waste service provision. *Bioresour. Technol.* **Jan. 2017**, *volume* 223, pp. 237–249. [doi: 10.1016/J.BIORTECH.2016.10.044]
31. Mattioli, A.; Gatti, G.B.; Mattuzzi, G.P.; Cecchi, F.; and Bolzonella, D. Co-digestion of the organic fraction of municipal solid waste and sludge improves the energy balance of wastewater treatment plants: Rovereto case study. *Renew. Energy* **2017**, *volume* 113, pp. 980–988. [doi: 10.1016/j.renene.2017.06.079]
32. Gray, D.M.D.; Suto, P.; and Peck, C. Anaerobic digestion of food waste: Funding opportunity no. EPA-R9-WST-06-004. , 2008. [Online]. Available: https://archive.epa.gov/region9/organics/web/pdf/ebmudfinalreport.pdf
33. Bernstad, A.; Malmquist, L.; Truedsson, C.; and la Cour Jansen, J. Need for improvements in physical pretreatment of source-separated household food waste. *Waste Manag.* **Mar. 2013**, *volume* 33, pp. 746–754. [doi: 10.1016/J.WASMAN.2012.06.012]
34. Sembera, C.; Macintosh, C.; Astals, S.; and Koch, K. Benefits and drawbacks of food and dairy waste co-digestion at a high organic loading rate: A Moosburg WWTP case study. *Waste Manag.* **Jul. 2019**, *volume* 95, pp. 217–226. [doi: 10.1016/j.wasman.2019.06.008]
35. Macintosh, C.; Astals, S.; Sembera, C.; Ertl, A.; Drewes, J.E.; Jensen, P.D.; and Koch, K. Successful strategies for increasing energy self-sufficiency at Grüneck wastewater treatment plant in Germany by food waste co-digestion and improved aeration. *Appl. Energy* **2019**, *volume* 242, pp. 797–808. [doi: 10.1016/j.apenergy.2019.03.126]
36. Cecchi, F. and Cavinato, C. Smart approaches to food waste final disposal. *Int. J. Environ. Res. Public Health* **2019**, *volume* 16, . [doi: 10.3390/ijerph16162860]
37. Evans, T.D. Domestic Food Waste – the Carbon and Financial Costs of the Options. *Munic. Eng.* **2012**, *volume* 165, pp. 3–10.
38. Zan, F.; Iqbal, A.; Guo, G.; Liu, X.; Dai, J.; Ekama, G.A.; and Chen, G. Integrated food waste management with wastewater treatment in Hong Kong: Transformation, energy balance and economic analysis. *Water Res.* **2020**, . [doi: 10.1016/j.watres.2020.116155]
39. Zan, F.; Liang, Z.; Jiang, F.; Dai, J.; and Chen, G. Effects of food waste addition on biofilm formation and sulfide production in a gravity sewer. *Water Res.* **2019**, *volume* 157, pp. 74–82. [doi: 10.1016/j.watres.2019.03.061]
40. Iqbal, A.; Ekama, G.A.; Zan, F.; Liu, X.; Chui, H.K.; and Chen, G.H. Potential for co-disposal and treatment of food waste with sewage: A plant-wide steady-state model evaluation. *Water Res.* **Oct. 2020**, *volume* 184, p. 116175. [doi: 10.1016/j.watres.2020.116175]
41. Bernstad Saraiva, A.; Davidsson, A.; and Bissmont, M. Lifecycle assessment of a system for food waste disposers to tank - A full-scale system evaluation. *Waste Manag.* **Aug. 2016**, *volume* 54, pp. 169–177. [doi: 10.1016/j.wasman.2016.04.036]
42. Davidsson; Bernstad Saraiva, A.; Magnusson, N.; and Bissmont, M. Technical evaluation of a tank-connected food waste disposer system for biogas production and nutrient recovery. *Waste Manag.* **Jul. 2017**, *volume* 65, pp. 153–158. [doi: 10.1016/j.wasman.2017.03.052]

43. Bolzonella, D.; Pavan, P.; Battistoni, P.; and Cecchi, F. The under sink garbage grinder: A friendly technology for the environment. *Environ. Technol.* **2003**, *volume* 24, pp. 349–359. [doi: https://doi.org/10.1080/09593330309385567]
44. Guven, H. and Ozturk, I. Impact of Food Waste Addition To Municipal Wastewater on Environmental Infrastructure. , in *6th Eur. Conf. Ren. Energy Sys.*, 2018. [Online]. Available: https://www.researchgate.net/publication/326571680_Impact_of_food_waste_addition_to_municipal_wastewater_on_environmental_infrastructure
45. NYC Department of Environmental Protection The impact of food waste disposers in combined sewer areas of New York City. , 1997.
46. Nilsson, P.; Hallin, P.O.; Johansson, J.; Karlén, L.; Lilja, G.; Pettersson, B.A.; and Pettersson, J. Källsortering med avfallskvarnar: En fallstudie i Staffanstorp (Source-separation with food waste disposers: a case study from Staffanstorp). , 1990.
47. Battistoni, P.; Fatone, F.; Passacantando, D.; and Bolzonella, D. Application of food waste disposers and alternate cycles process in small-decentralized towns: A case study. *Water Res.* **2007**, *volume* 41, pp. 893–903. [doi: 10.1016/j.watres.2006.11.023]
48. Bernstad, A.; Davidsson, å; Tsai, J.; Persson, E.; Bissmont, M.; and la Cour Jansen, J. Tank-connected food waste disposer systems - Current status and potential improvements. *Waste Manag.* **Jan. 2013**, *volume* 33, pp. 193–203. [doi: 10.1016/j.wasman.2012.09.022]